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PERFORMANCE EVALUATION OF A
PASSIVE MICROWAVE IMAGING SYSTEM

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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HOUSTON, TEXAS 77058

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**PERFORMANCE EVALUATION OF A
PASSIVE MICROWAVE IMAGING SYSTEM**

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PERFORMANCE EVALUATION OF A PASSIVE MICROWAVE IMAGING SYSTEM

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SUMMARY

The Passive Microwave Imaging System is a new remote sensing instrument in the microwave (10.69 gigahertz) region for application to Earth observations. A test program was conducted to evaluate the operational performance of the system for potential application to Earth resources measurements. The image quality was found to be poor when compared with photographs and infrared images of the same flight lines; however, the quality is adequate for remote sensing applications studies. Problems with cross-polarization, antenna side lobes, and geometric correction of the scan were identified in the analysis. These problems can be improved by modifications of the programming in the software. Evaluation of the images shows sufficient response and resolution for possible application to hydrology for soil moisture studies, to sea state monitoring for storm forecasting, and to sea ice mapping for scientific studies of ice dynamics.

INTRODUCTION

The test site for the Passive Microwave Imaging System (PMIS) was the area surrounding the Lyndon B. Johnson Space Center (JSC) and neighboring Clear Lake. The JSC-Clear Lake area was selected because it contains several land-water interfaces (for high contrast of brightness temperatures) to test spatial resolution and geometric fidelity of the PMIS images. The area is also near Ellington Air Force Base (EAFB) where the JSC remote sensing flights originate and can be used for later "functional check flights" of the PMIS instrumentation. As part of the Houston Area Test Site (HATS), the test site was readily accessible for ground truth measurements.

The target was flown May 18, 1972, on orthogonal flight lines at altitudes of 610, 1220, 2440, and 4880 meters (2000, 4000, 8000, and 16 000 feet). Weather conditions during the 4-hour flight was ground haze and very light, scattered clouds at approximately 2440 meters (8000 feet) during the 4880-meter (16 000-foot) pass.

The PMIS was operated in the NASA NP3A aircraft and the data were recorded on magnetic tape. To provide image comparison and geometric measurements, the RC-8 camera with SO 397 film and the 8- to 14-micrometer channel of the RS-14 infrared (IR) scanner were operated simultaneously with the PMIS. The PMIS data were processed through the PMIS/Data Analysis System (DAS), which produces false color images from the brightness temperature at each beam position.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

INSTRUMENTATION AND RELATED FACTORS

The instrumentation and ground support equipment for the PMIS are described in detail in reference 1; only a brief description of the equipment is given here for clarity. The airborne portion of the system consists of the antenna, radiometers, and the control/monitor console, which are mounted in the NASA NP3A aircraft.

The antenna is a phased array with vertical and horizontal polarization channels and is electronically stepped for scanning. The antenna scans conically at 50° incidence angle with the ground and 33° to either side of the flightpath. A total of 44 beam positions are recorded on each conical scan. A separate radiometer is used for the vertical and horizontal channels. The two radiometers simultaneously measure the brightness temperature in both polarizations at each beam position. Two hot loads are used for calibration at the completion of each scan. An onboard monitor displays a television (TV) image of a radiometer output in 16 shades of gray. The black and white TV image is recorded on 35-millimeter film. The radiometer data and pertinent aircraft data (position, altitude, heading, roll, pitch) are recorded on magnetic tape for later processing by the ground station.

The JSC-Clear Lake test site and flight lines are shown in figure 1. The orthogonal flight lines determine if the view angle or other factors affect the vertically and horizontally polarized images. The lines were flown at altitudes of 610, 1220, 2440, and 4880 meters (2000, 4000, 8000, and 16 000 feet). The increasing altitude over the same target determines geometric fidelity, spatial resolution, and optimum altitude to fly various types of targets.

The RC-8 metric mapping cameras were used to record photographic images of the flight lines at altitudes of 4880 and 1220 meters (16 000 and 4000 feet) for evaluation of PMIS images for geometric fidelity.

The photographs taken at 4880 meters (16 000 feet) have approximately the same scale as the PMIS images at 610 meters (2000 feet). Operating simultaneously with the PMIS, the RS-14 infrared imaging scanner was used to record IR (8 to 14 micrometer) images in black and white of the flight lines. The thermal IR images were used for comparison with the PMIS images and for interpretation of the microwave data.

Weather conditions in the test area during data collection (very thin scattered clouds at 2440 meters (8000 feet) and ground haze) slightly degraded the photographs but no degradation is evident on the IR and microwave images. Significant degradation is not expected until the water content of the clouds becomes high for the relatively long wavelength (2.8 centimeters) of the PMIS.

A ground microwave radiometer was not available to measure the emissivity in the microwave region of the targets as part of the ground truth measurements. The brightness temperature comparisons used in this evaluation are based on previous measurements contained in references 2 through 5.

GROUND DATA STATION

The Microwave/Multispectral Ground Data Station was manufactured as PMIS ground support equipment for producing images of the microwave temperature measurements. The station consists of an analog tape recorder/reproducer; a special computer interface to read in pulse-code-modulation (PCM), PMIS, and analog data analysis system (ADAS) data; an SEL 810 computer; three nine-track drives; and teletype for data input and processing. The data display is by color cathode ray tube (CRT), a high-resolution color-film recorder, or a line printer that prints the brightness temperature at each beam position. For operator communication with the computer, an alphanumeric keyboard with CRT display is used to change color scales, limits, displays, et cetera.

A computer program (EXTRACT) is available to review the data directly from the analog tape; however, it is slow, and the PCM data are first converted to nine-track digital tape for more rapid data processing in the computer. The data are then ready for computer manipulation to obtain the best images or to enhance certain features such as water, land, vegetation, et cetera. The color displays are capable of producing false color images of the brightness temperatures in 64 colors. Existing color tables are available in the EVAL computer program, or the investigator can devise special color tables. Special color tables were constructed for displaying the JSC-Clear Lake area flight lines.

DATA ANALYSIS

The data were reviewed on the day of the flight to determine whether or not good data were obtained. This procedure uses the flight analog tape, which is processed very slowly on the DAS. The PMIS and ADAS data were then transferred to nine-track digital tape to increase the efficiency of run time on the DAS, because the processing and rewind time are much faster than that for the analog tape. The data were reviewed using various color tables to achieve images with nonambiguous colors. No colors are repeated in the table, and an attempt was made to make water blue and grass green to facilitate interpretation. The flight lines were then reviewed using the special color table to determine the temperature limits that would best display the data. The technique that proved most effective was to use three sets of limits on most flight lines to achieve the best spatial resolution in the images. One set of limits was used for vertical, horizontal, and difference images to display the wide range of brightness temperatures (land and water) measured on one flight line. To gain better resolution and enhance land features, a second set of limits was required that displayed water as black and destroyed the detail in the water. The third set was for low brightness temperatures to get detail in the water, but all land detail or high temperatures were lost. On all flight lines containing a wide range of brightness temperatures, three sets of images were required to obtain maximum image resolution.

The 64 available colors were not used for this analysis because the average eye cannot distinguish all the color shades. The color table is set up for 50 colors with the cluster of brightness temperatures for water and land using $1/64$ increments and the temperatures in between using $1/32$ increments of the 64 available. This allows more resolution where required without the use of ambiguous color shades. The CRT difference image uses 16 shades of green plus red and black for a total of 18 colors. The red was set so that when the horizontal channel temperature was greater than the vertical channel temperature, a red color would appear on the difference image. For most objects, the brightness temperature of the vertical channel is greater than that of the horizontal channel. However, the color recorder malfunctioned and displayed some greens as blue, and the film images are unsatisfactory although the CRT display was correct. Any color table can be devised to interpret a given set of data or to suit the preferences of the investigator.

The thermal IR image of the target area shown in figure 2 was obtained with the RS-14 scanner at a 4880-meter (16 000-foot) altitude. Color photographs were also obtained with the RC-8 camera, but the 22.86- by 22.86-centimeter (9- by 9-inch) film format is too large for this report. Figures 3(a), 3(b), and 3(c) show PMIS images obtained simultaneously with the image in figure 2. Figure 3(d) shows the PMIS

images obtained on flight lines 6, 8, and 9. Clear Lake, Galveston Bay, and the upper portion of Clear Creek are fairly obvious in the images, but other features are not easily identified from the 4880-meter (16 000-foot) altitude. The scan angle of the PMIS is 50° or 1.2 times the altitude forward of the aircraft, which must be considered when operating the instrument. The forward scan angle caused the flight line irregularities in figures 3(a) and 3(b).

A problem with uniform brightness temperature across the scan is obvious in the Galveston Bay images (figs. 3(a) and 3(b)). The measured brightness temperature is not constant across the scan of the antenna for either channel although the water is essentially a uniform target. The horizontal channel measured the water 20 K colder in the center of the scan than at the edge, and the vertical channel measured the water 6 K colder at the edge of the scan than in the center. This caused nonuniform coloring of the water images across the flight line. This problem is not evident on the land images because of nonuniformity of the target. Figures 4 and 5 are plots of the computer printout of the brightness temperature of the water in Galveston Bay in the horizontal and vertical channels of the PMIS. The points are the average of 25 data points at each beam position, and the bars represent the range of temperature measured at each beam position.

The accuracy can be improved by scanning a target of known constant brightness temperature (such as the Gulf of Mexico) under clear skies and calm water conditions and by adjusting the computer program loss corrections to obtain a constant temperature at the output. The current computer corrections are primarily based on laboratory-measured losses in the antenna, radome, and wave guides, whereas the proposed method would include all losses and cross-polarization encountered when the instrument is mounted and operating in the aircraft. The computer program described in reference 6 can also be used to calculate the theoretical brightness temperature of the water at the time of the flight.

Antenna side-lobe problems are also evident in the images when a target in the side lobes is much warmer or colder than in the center of the antenna pattern. Figure 6 demonstrates the image degradation caused by a cold water target or a warm land target in the antenna side lobes. The water is Clear Lake and Galveston Bay, but the contribution from the side lobes increases the apparent brightness temperature of the water and produces streaks in the image. The water of Galveston Bay also causes the shore to appear colder when it is in the side lobes. Antenna side-lobe contributions are not easily eliminated and should be considered when setting up flight lines and interpreting the PMIS data.

Some cross-polarization occurs at the antenna, but it is not easily identified in the images. Some side lobe and cross-polarization can be corrected in the software program, but additional testing of the instrument

with known targets is necessary to obtain the proper correction factors and define the data-processing techniques.

Another problem with the images that can be corrected in the DAS programing is the geometric distortion of the image. The DAS takes the antenna groundtrack that is 50° incidence angle and 33° to either side of the flight line and converts each beam position to an image that is directly beneath the aircraft. The images, however, retain the arc of the scan that geometrically distorts the targets. The geometric distortion is particularly evident on streams, rivers, and shorelines. The image will distort slight bends or arcs into straight lines and straight lines into arcs, which could be a problem if geometric fidelity is important to the investigator. A reexamination of the geometrical corrections that are included in the software program might eliminate the image distortion caused by the scan arc.

Figures 7 and 8 demonstrate some of the geometric distortion of the scan at the 1220-meter (4000-foot) altitude. The IR image in figure 7 is included for comparison. The water and wet areas around Clear Creek have low emissivity and are colder in the microwave than the surrounding land and appear blue and yellow in the image. The metal storage tanks and water inside the fire control embankments of the Webster tank farm also have lower microwave emissivity than the surrounding land and appear cold in the microwave image. The roofs of buildings appear warm in the IR images and warm in the vertical polarization but appear cold in the horizontal polarization of the PMIS images. Metallic roofs sometimes show the reverse in the polarized images.

Figure 9 shows images of the Webster tank farm from the 610-meter (2000-foot) altitude. The footprint of the beam positions is smaller in area at the lower altitude, and the individual metallic tanks are beginning to be resolved. The distortion of Clear Creek by the scan arc is evident in these images.

Figure 10 is an IR image and a PMIS image of the Lyndon B. Johnson Space Center, the west end of Clear Lake, and part of Nassau Bay from an altitude of 610 meters (2000 feet). Much better resolution of the water is evident because of the high contrast in land and water emissivity, and the beam footprint covers a relatively small area (68.6 by 33.5 meters (225 by 110 feet)). The difference in the vertical and horizontal polarization on the building roofs is also demonstrated. Figure 11 shows that the PMIS will produce geometrically correct images of targets with high-contrast brightness temperatures from a low altitude (target size large compared to size of PMIS footprint).

Red Fish Island in Galveston Bay was imaged at altitudes of 4880, 2440, and 610 meters (16 000, 8000, and 2000 feet). The 1220-meter (4000-foot) altitude pass missed the island, and no image was obtained. The island was integrated into the background water at 4880 meters

(16 000 feet) (figs. 3(a) and 3(b)). The island is just resolved in the 2440-meter (8000-feet) image and is fairly well defined in the image from 610 meters (2000 feet) (fig. 12). The island is approximately 1524 meters (5000 feet) long and 183 meters (600 feet) wide at the widest point. The geometry of the island is not accurately reproduced because the beam footprint is too large, even at 610 meters (2000 feet), for accurate geometric reproduction.

The test site was flown on north/south and east/west flight lines to determine if any viewing angle effects were present. No depression angle effects are evident in the images; however, there are antenna side-lobe problems that can be minimized by proper selection of flight lines and flight direction.

The computer program for the PMIS/DAS has cursor and zoom capability to select a given area in an image and magnify it for more detailed examination. The zoom only increases the size of the individual increments or the beam position area; this increase in size does not increase resolution and makes interpretation more difficult in most cases.

CONCLUSIONS AND RECOMMENDATIONS

The flight conducted for this performance evaluation is sufficient to identify some problems, to indicate possible improvement in software performance, and to suggest potential application of the Passive Microwave Imaging System (PMIS) data. Additional flights are required to determine loss corrections, performance through cloud cover, and applications as an Earth resources instrument. The images over Galveston Bay show that non-uniform brightness temperatures are obtained across the scan. The horizontal channel measures the center of the scan 20 K colder than at the edge. The vertical channel measures 6 K colder on the edge of the scan than in the center. The average horizontal channel brightness temperature of Galveston Bay measured by the PMIS is 58 K, whereas the published microwave temperature for seawater is approximately 80 K for horizontal polarization. The horizontal channel of the PMIS probably measures lower than it should. The PMIS vertical channel measured an average of 148 K in Galveston Bay, and the published value for seawater is approximately 155 K, which is within experimental error. It is recommended that the PMIS be flown over open ocean on a calm, cloudless day for a uniform target to determine the loss corrections required to obtain a uniform brightness temperature at all beam positions for the output of the PMIS Data Analysis System. The PMIS can be flown over the Gulf of Mexico at low altitude with the shell tower in the flight line for surface parameter measurements. (Contiguous scans are not required.) The flight should be upwind, downwind, and crosswind in both directions to eliminate any wave effects. These data would then be used to modify the PMIS Data Analysis

System program for new loss correction factors to achieve a constant brightness temperature at each beam position in a scan.

The temperature accuracy on a PMIS image is a function of several parameters: accuracy of loss corrections, antenna side lobes, cross-polarization, accuracy of rectified image, et cetera. The temperature accuracy is therefore strongly dependent on the target and flight line. The images accumulated during this flight indicate that the best accuracy obtained is approximately 20 K. The accuracy would improve to approximately 3.5 K with the proposed software corrections.

Antenna side lobes and cross-polarization also degrade the image but are not easily identified or corrected. Careful selection of flight lines could overcome part of the problem by eliminating objects from the side lobes that are significantly different in temperature from the target, such as land from a water target and water from a land target. Modification is required in the software programming to correct for antenna side-lobe and cross-polarization contributions to the apparent brightness temperature of a target.

The scan arc introduces distortion in the images and degrades the geometric fidelity. The software corrections from a 50° incidence angle with the ground to a rectified image should be reexamined to determine if improvement is possible. The scan arc appears in all images and degrades the geometric resolution.

Test sites and flight lines containing small objects of interest and a wide range of emissivities must be flown at minimum altitude if geometric fidelity and spatial resolution are important. The PMIS beam position footprint size must be three to five times smaller than the object of interest if a good image is to be achieved. The minimum altitude with the NP3A aircraft and the velocity/altitude ratio of the PMIS is 548 to 610 meters (1800 to 2000 feet). As the object size increases or the geometric fidelity requirement decreases, the altitude can be increased.

No Earth resources applications of the PMIS were proven by this performance evaluation flight, but remote sensing of soil moisture, sea state, and sea ice appear promising. Additional application-oriented evaluation flights are required for quantitative information on specific applications of the PMIS as a remote sensor.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, November 27, 1973
640-01-01-00-72

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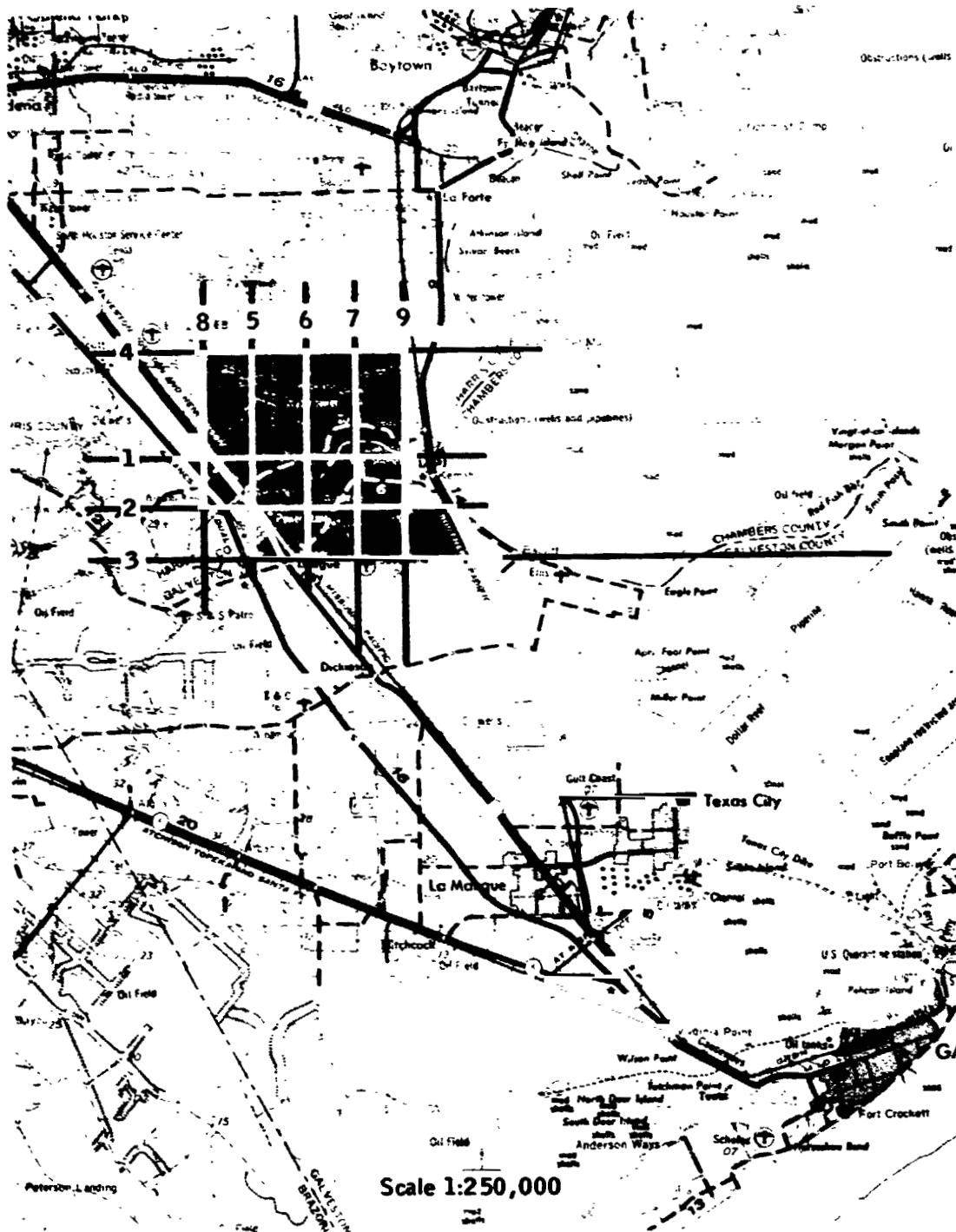


Figure 1.- The JSC-Clear Lake test site showing flight lines used for collection of the PMIS performance evaluation data.



Figure 2.- Image of JSC-Clear Lake area obtained by RS-14 scanner from 4880-meter (16 000-foot) altitude on May 18, 1972. The light areas are higher in equivalent blackbody temperature.

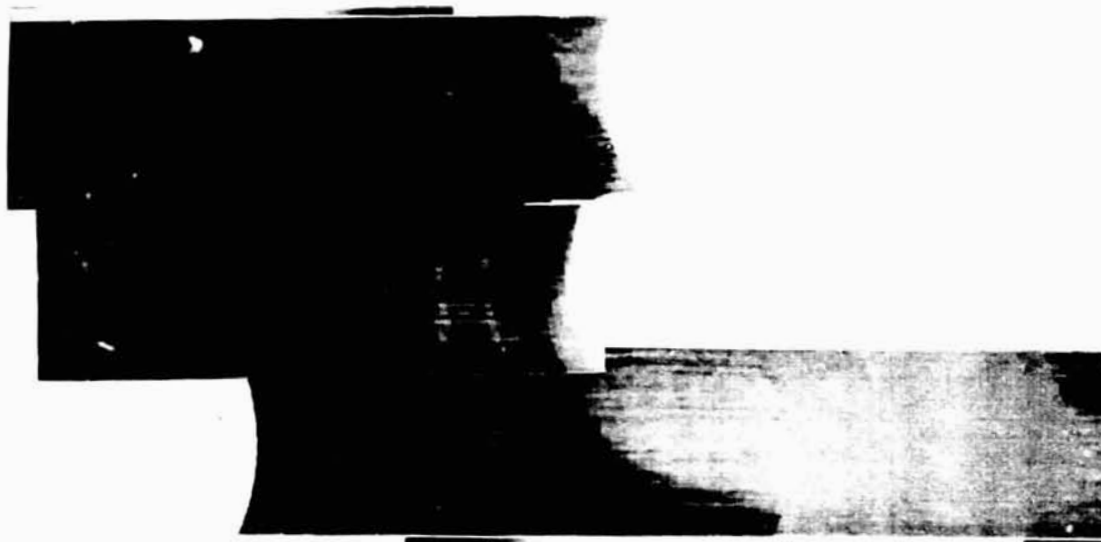


(a) Vertical channel image. Clear Lake is in the center with Galveston Bay on the right. Temperature limits are 150 (black) to 300 K (white). (Note the brightness temperature anomaly in bay water.)



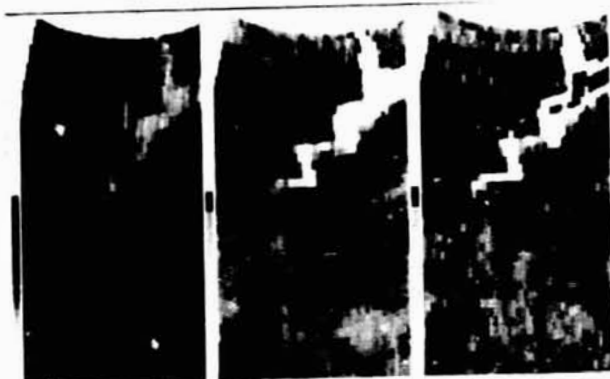
(b) Horizontal channel image. Clear Lake is in the center with Galveston Bay on the right. Temperature limits are 70 to 300 K. (Note the brightness temperature anomaly in bay water.)

Figure 3.- The PMIS images obtained from a 4880-meter (16 000-foot) altitude over the JSC-Clear Lake test site. These images were obtained simultaneously with the RS-14 scanner image in figure 2.



(c) Difference image. Film processing has resulted in blue coloring that should be green (not obvious in black and white print). The image is composed of the difference between the vertical and horizontal channel measurements. Temperature limits are 70 to 170 K.

Figure 3.- Continued.



Line 6

Vertical limits (right):

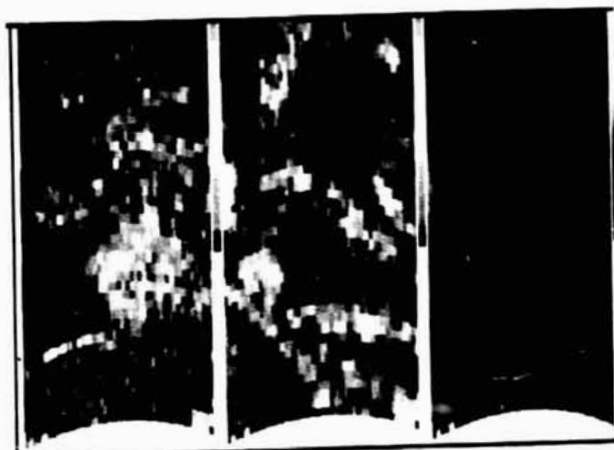
190 to 300 K

Horizontal limits (center):

150 to 290 K

Difference limits (left):

79 to 149 K



Line 8

Vertical limits (left):

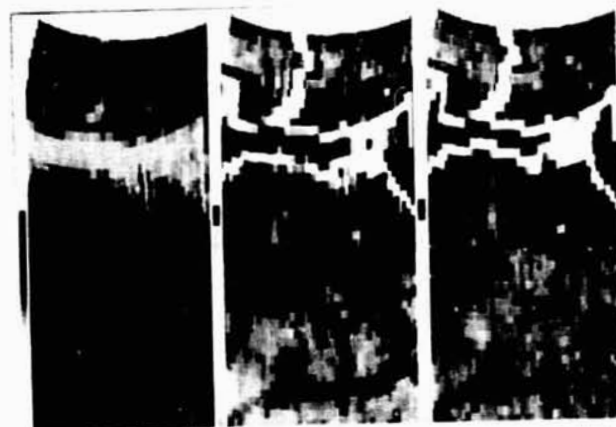
250 to 290 K

Horizontal limits (center):

235 to 285 K

Difference limits (right):

82 to 142 K



Line 9

Vertical limits (right):

190 to 300 K

Horizontal limits (center):

150 to 290 K

Difference limits (left):

79 to 149 K

(d) Flight lines 6, 8, and 9 (fig. 1) as imaged by the PMIS.
Clear Lake is the body of water in the bottom frame.

Figure 3.- Concluded.

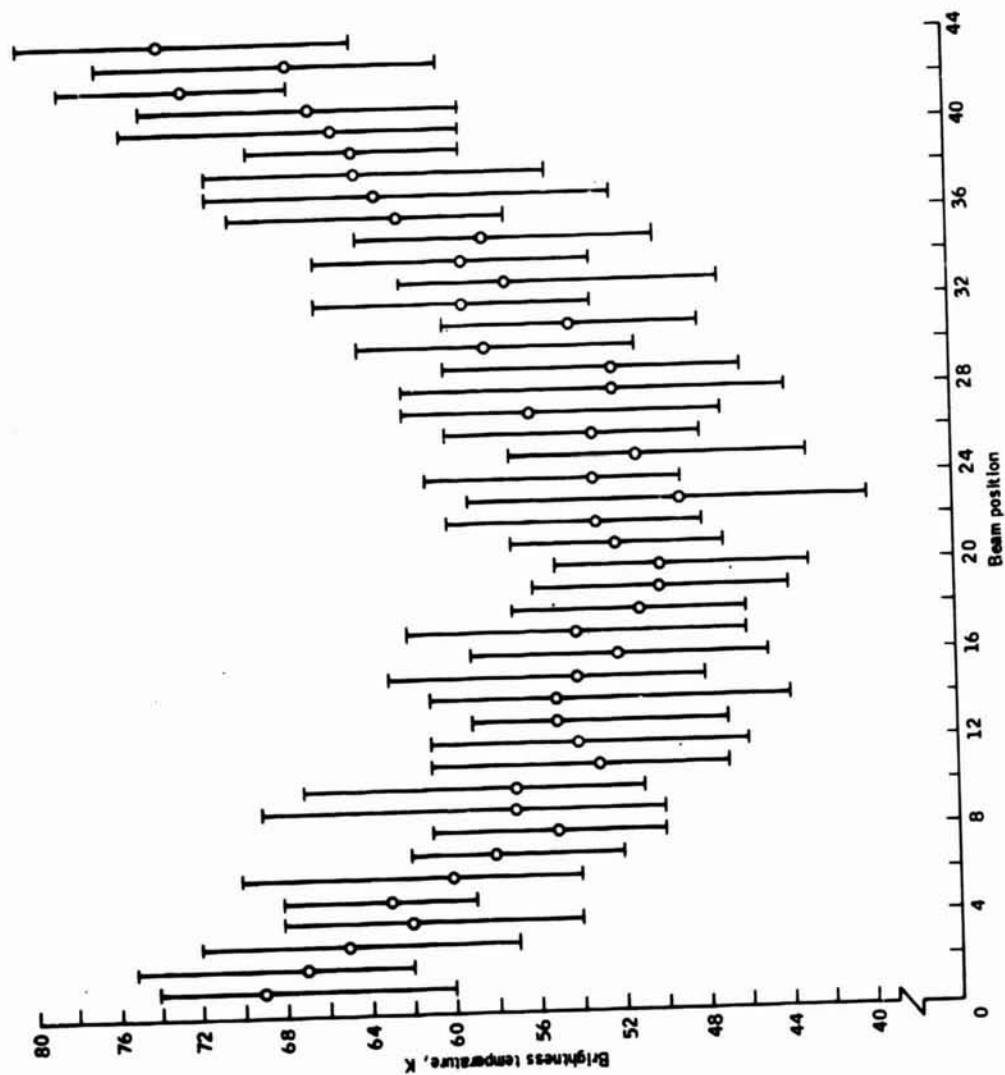


Figure 4.- Average brightness temperature of horizontal polarization channel for 25 scans of Galveston Bay. (Bars show range of readings at each beam position.)

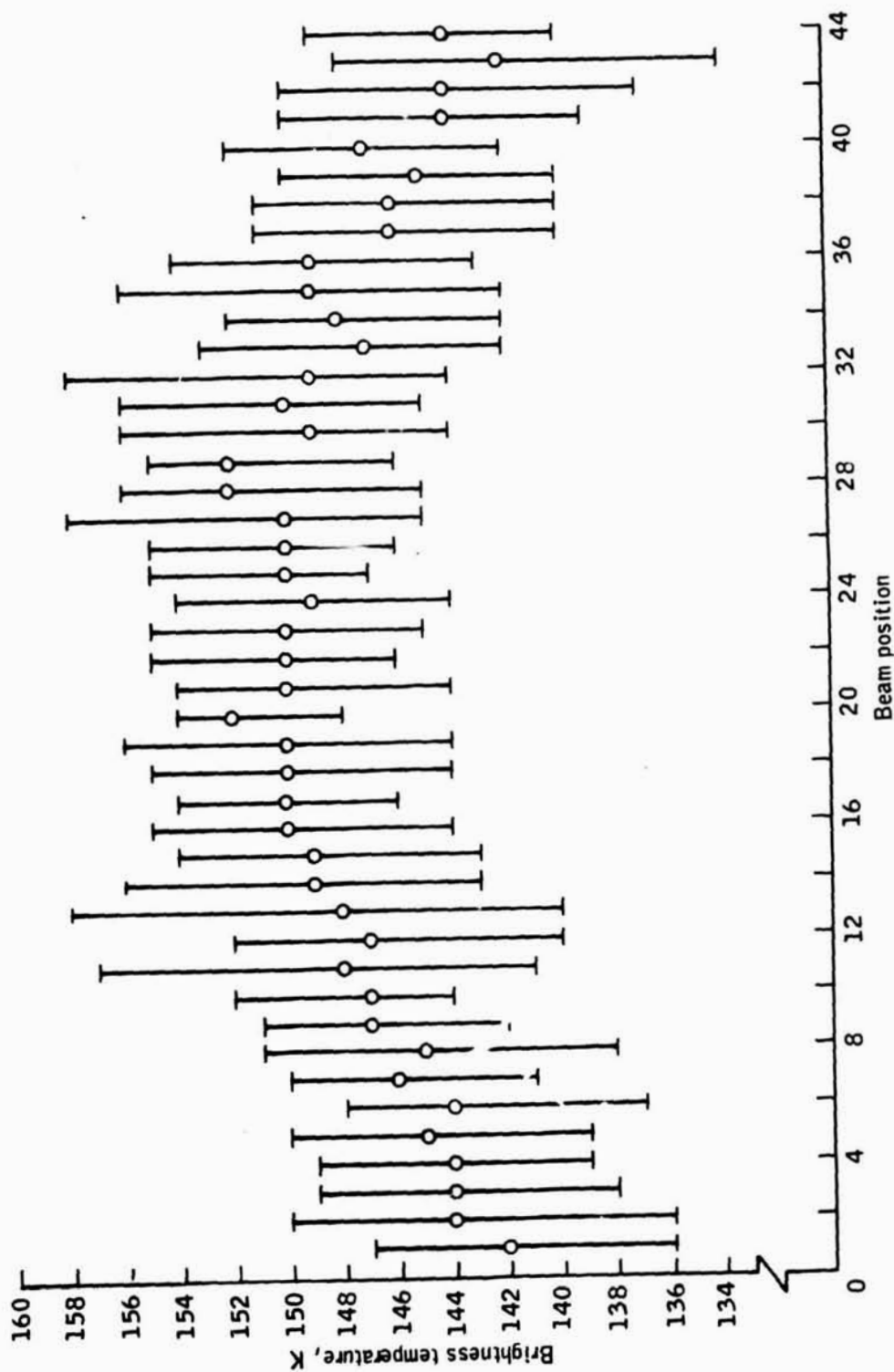
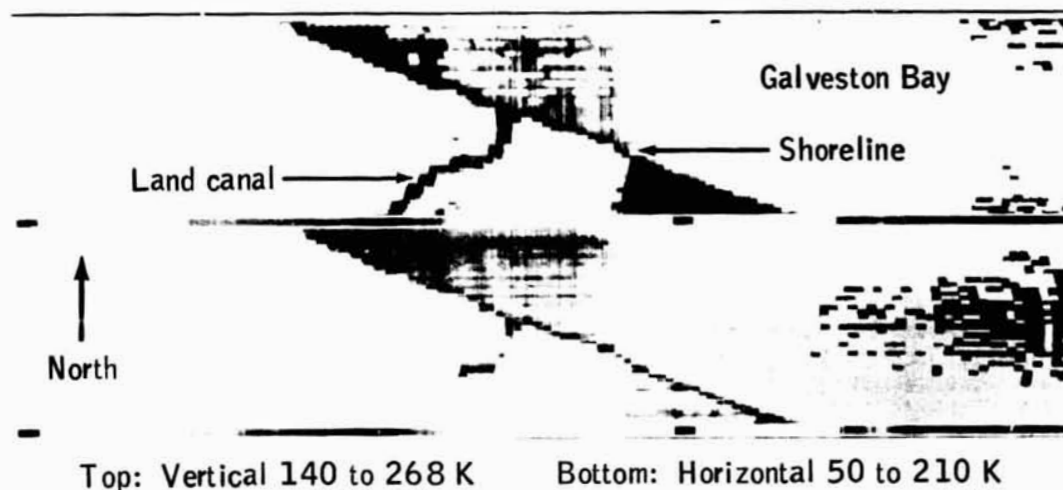
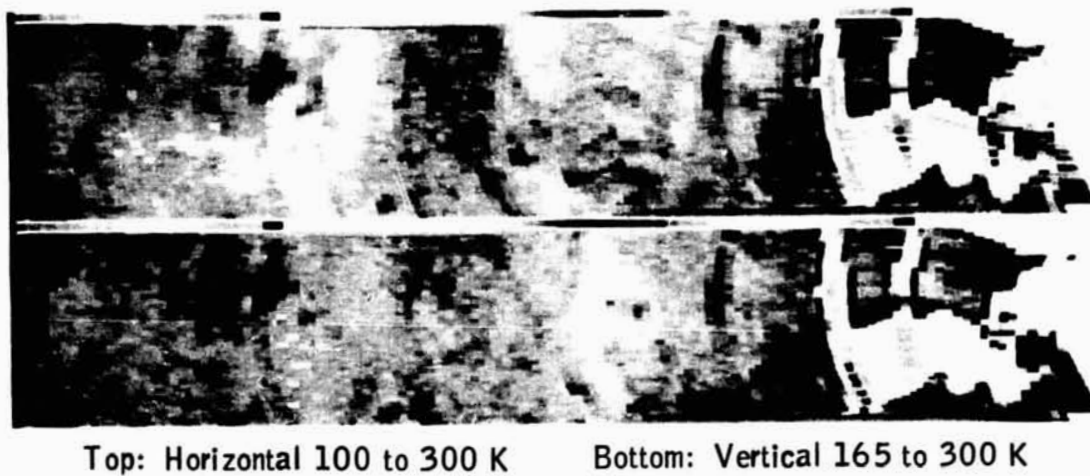


Figure 5.- Average brightness temperature of vertical polarization channel for 25 scans of Galveston Bay. (Bars show range of readings at each beam position.)



- (a) Galveston Bay shoreline showing antenna side-lobe anomalies of the land and water. The warmer water of the canal changes the brightness temperature in the outlet fan but not over the large area shown.



- (b) Water of Clear Lake showing influence of warmer land in the antenna side lobes.

Figure 6.- The antenna side-lobe effect on PMIS images.

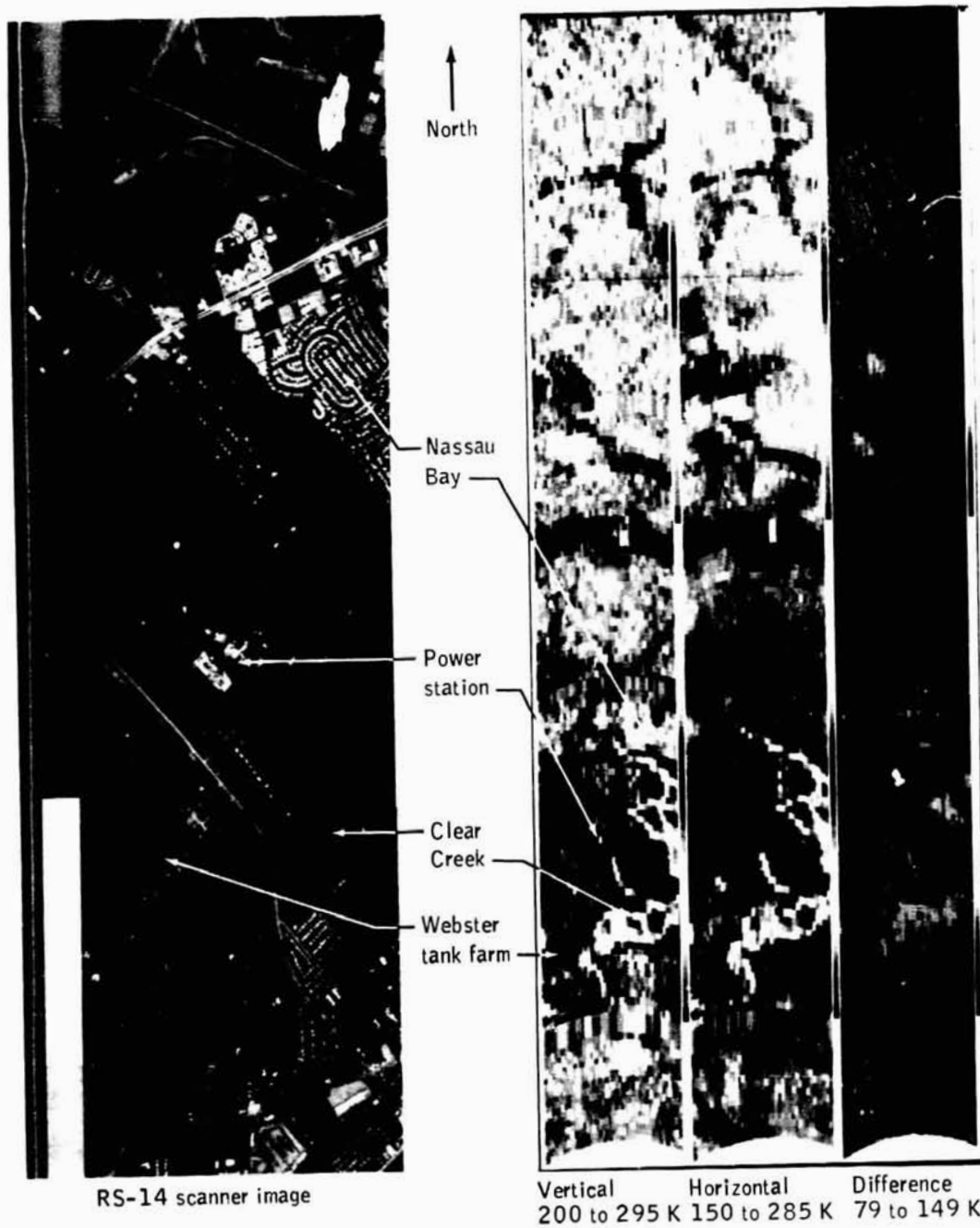


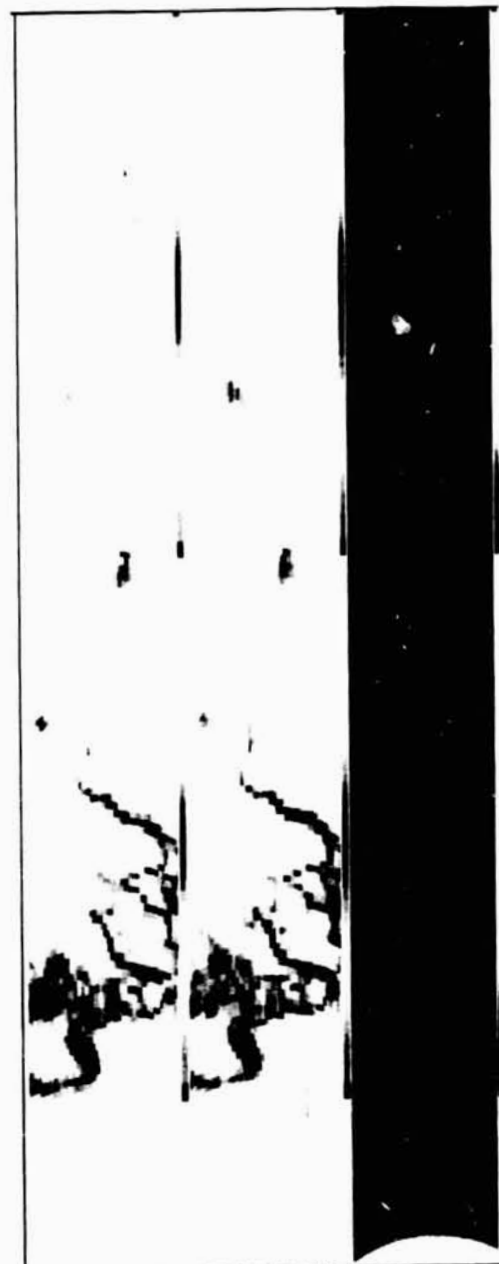
Figure 7.- Infrared (IR) and PMIS images of Webster tank farm and Clear Creek from a 1220-meter (4000-foot) altitude (average size of the PMIS beam position footprint, 137.2 by 68.6 meters (450 by 225 feet)).



Vertical Horizontal Difference
240 to 292 K 195 to 298 K 70 to 170 K

Land definition

↑
North



Vertical Horizontal Difference
150 to 280 K 85 to 255 K 50 to 198 K

Water definition

Figure 8.- The PMIS images of JSC and Clear Lake with different temperature limits to enhance warm and cold features (altitude, 1220 meters (4000 feet)).

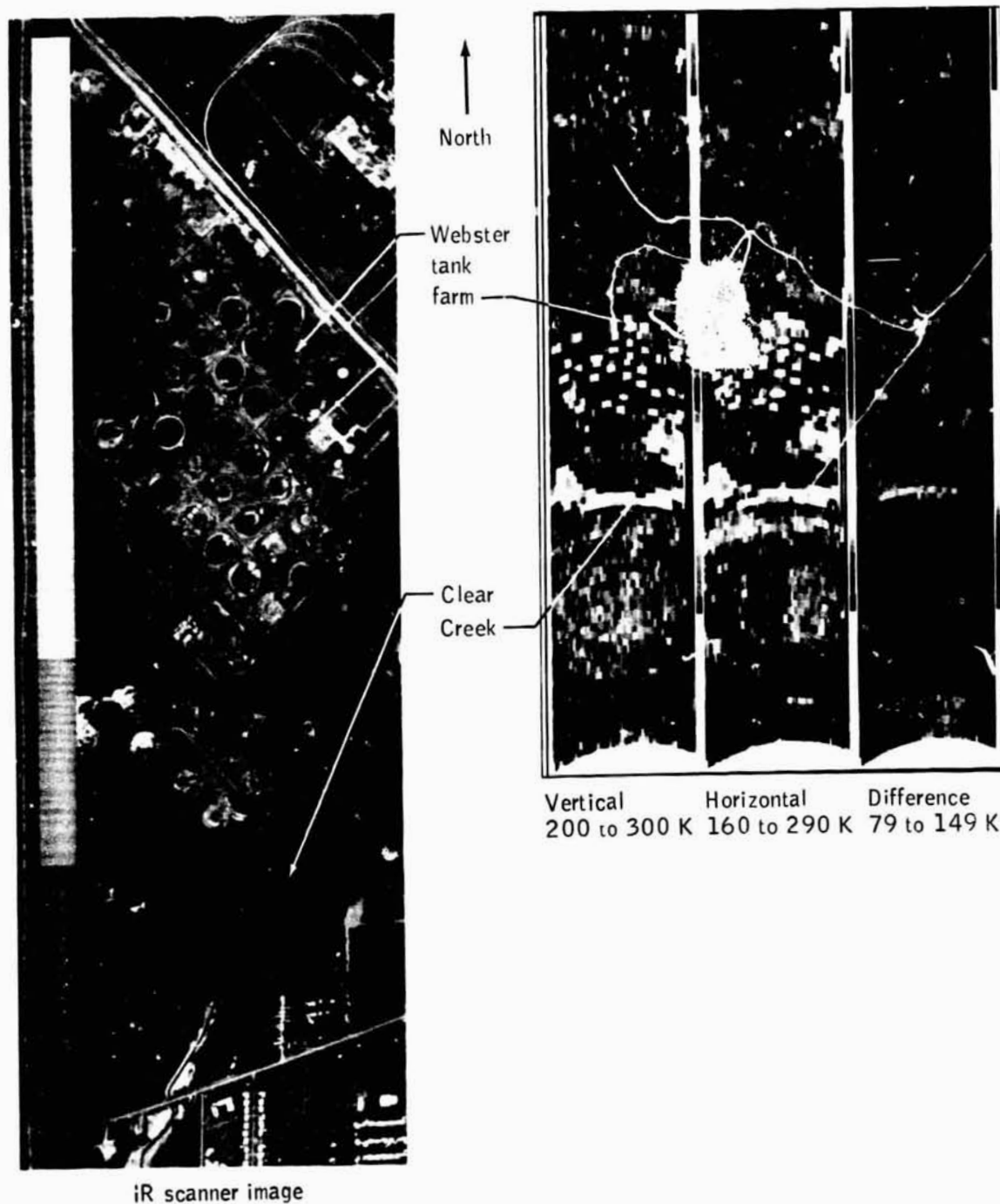


Figure 9.- Infrared (IR) and PMIS images of Webster tank farm and Clear Creek from a 610-meter (2000-foot) altitude (average size of PMIS beam position footprint, 68.6 by 33.5 meters (225 by 110 feet)).

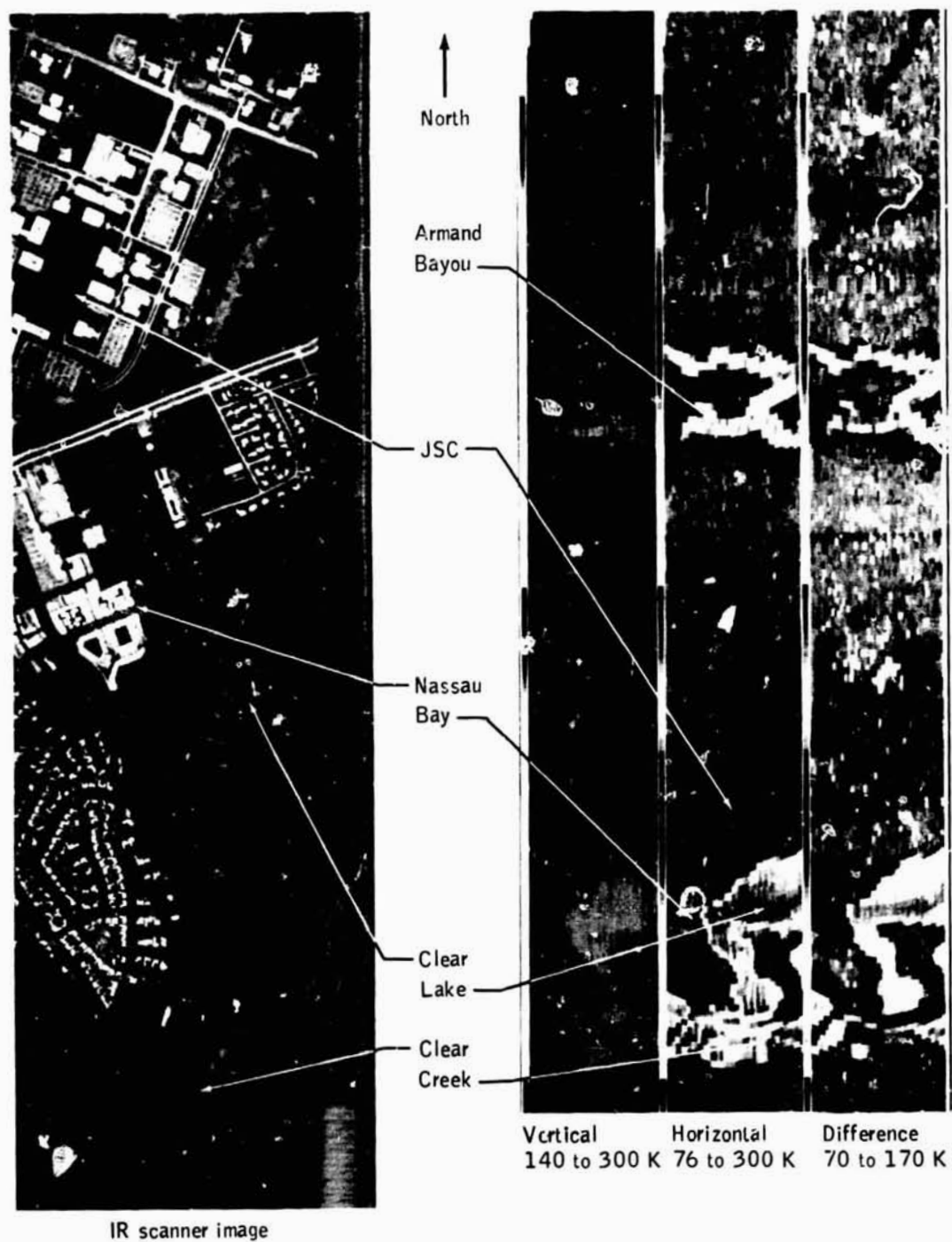


Figure 10.- Infrared (IR) and PMIS images of Clear Lake and JSC from a 610-meter (2000-foot) altitude. Temperature limits on PMIS images set for maximum overall definition.

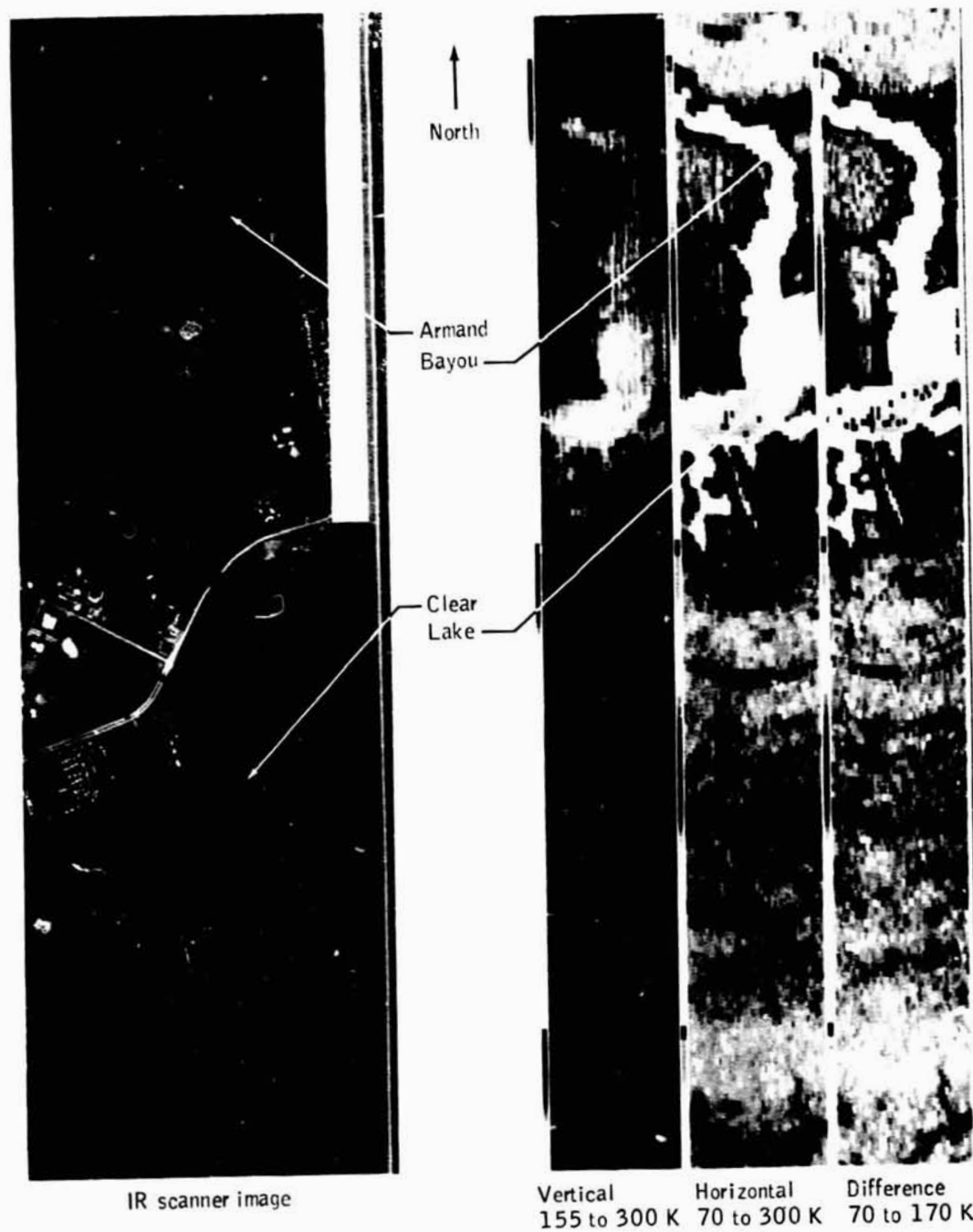


Figure 11.- Infrared (IR) and PMIS images of Clear Lake, demonstrating geometric fidelity of PMIS on high contrast targets (altitude, 610 meters (2000 feet)).



(a) Image from a 2440-meter (8000-foot) altitude (average size of PMIS beam position footprint, 274 by 137 meters (900 by 450 feet)).



(b) Image from a 610-meter (2000-foot) altitude (average size of PMIS beam position footprint, 68 by 34 meters (225 by 110 feet)).

Figure 12.- The PMIS images of Red Fish Island.